

# High-Frequency Surface Acoustic Wave Propagation in Nanostructures Characterized by Coherent Extreme Ultraviolet Beams

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## **Abstract**

We study ultrahigh frequency surface acoustic wave propagation in nickel-on-sapphire nanostructures. The use of ultrafast, coherent, extreme ultraviolet beams allows us to extend optical measurements of propagation dynamics of surface acoustic waves to frequencies of nearly 50 GHz, corresponding to wavelengths as short as 125 nm. We repeat the measurement on a sequence of nanostructured samples to observe surface acoustic wave dispersion in a nanostructure series for the first time. These measurements are critical for accurate characterization of thin films using this technique.

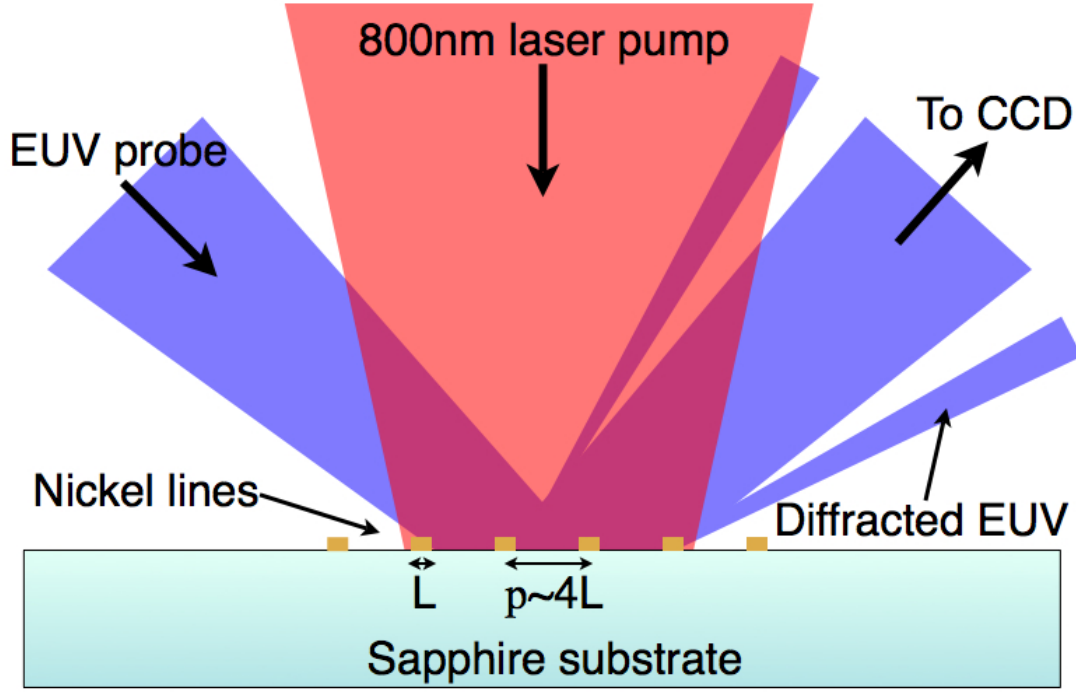
Monitoring surface acoustic wave (SAW) propagation is a powerful tool for studying the properties of thin films, surfaces, and interfaces. SAW modes have a very shallow surface penetration, and thus their propagation is sensitive to surface structure and composition. To study films of sub-micron thickness, however, it is necessary to use SAWs with comparably short wavelengths, since the penetration depth  $\zeta$  of the SAW is proportional to the acoustic wavelength  $\Lambda$  i.e.  $\zeta = \Lambda/2\pi$ . This presents a challenge for conventional optical methods of creating and detecting SAWs. Although it is quite straightforward to manufacture a sub-100nm thickness film, thermally exciting the film using a visible light interference pattern in a transient grating geometry is limited to SAW wavelengths in the range of optical wavelengths. As a result, the shortest acoustic wavelength generated to-date using the transient grating method is approximately 750nm [1, 2].

An alternative approach that overcomes this limitation is to lithographically pattern a nanostructure on the surface. This pattern can then be optically excited, locally stressing a surface and thus exciting a SAW with a wavelength limited only by the resolution of the lithographic pattern [3, 4]. However, this approach raises the question of how much the presence of the nanostructure will affect the propagation of the SAW. This question is critical for analysis of the underlying sample characteristics. Past measurements employing thin Al patterned absorbers suggested that these issues can be neglected [4-6]. However, these conclusions were based on data taken at a single SAW wavelength. To date, no work has sampled the full dispersion curve of a patterned thin film in order to come to a definitive conclusion on this issue.

Detection of very short-wavelength acoustic SAWs is also an issue. Visible light will not diffract from a sub-wavelength structure, so current techniques measure very small ( $<1$  part in  $10^5$  [7]) changes in surface reflectivity to observe SAW propagation [4-6]. However, these

reflectivity changes arise from a complex mix of thermal density changes and local and interfacial stresses and strains. Direct transient grating diffraction from the surface would give more reliable and easier-to-interpret data – however, such an experiment requires coherent light with a wavelength shorter than the SAW wavelength. For high frequencies, this corresponds to the extreme ultraviolet (EUV) region of the spectrum. In previous work, we demonstrated that coherent EUV beams can very sensitively probe acoustic-induced surface displacements with sub-picometer displacement resolution [8]. In that experiment, changes in the EUV diffraction were due to thermal and acoustic surface displacement, while temperature and stress-induced changes in reflectivity were negligible at the EUV wavelengths used ( $\sim 29\text{nm}$ ) [8].

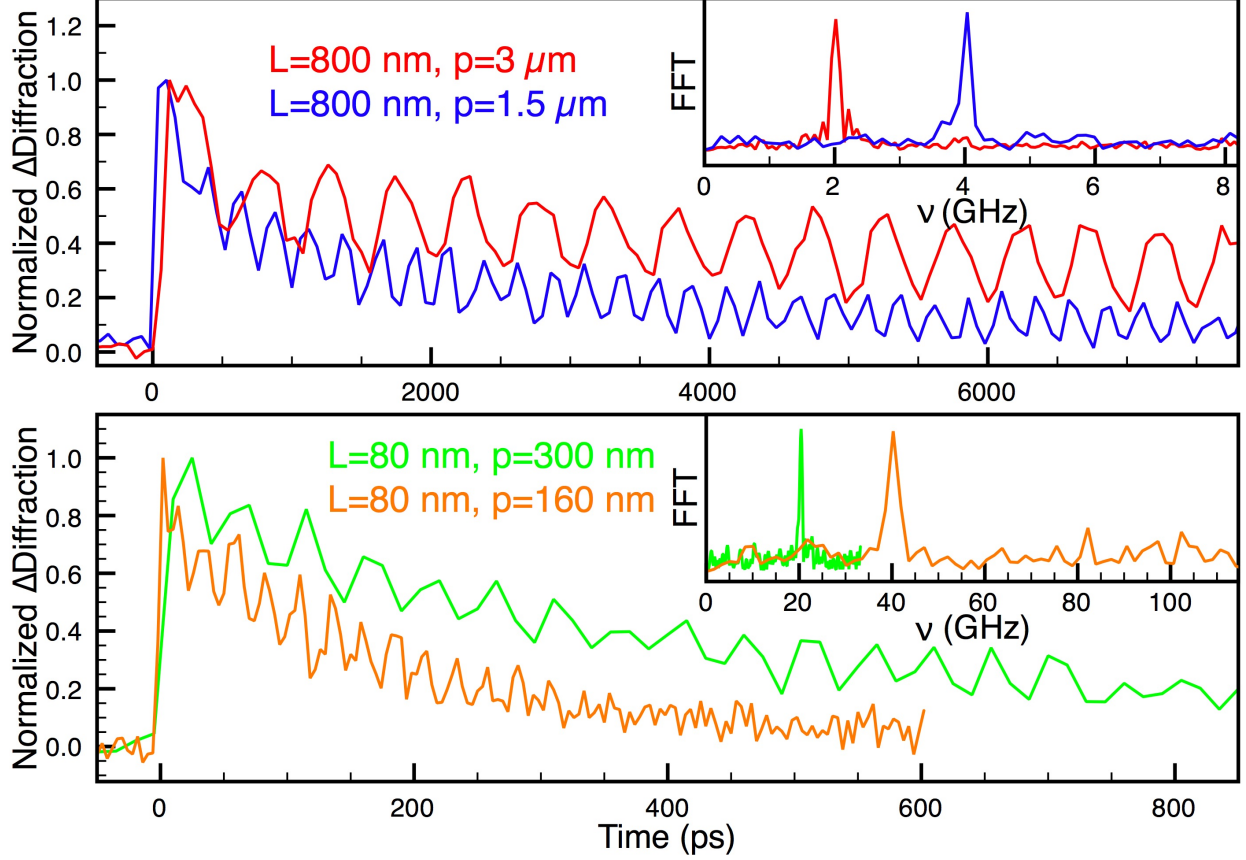
In this work, we excite a series of nickel-on-sapphire nanostructures using a Ti:sapphire laser, to generate high-frequency acoustic waves. We study the SAW propagation in the nanostructures by observing the changing diffraction intensity of an EUV probe beam (see Fig. 1). We observe the highest-frequency SAW dynamics to-date and demonstrate a first measurement of SAW dispersion in these nanostructure/bulk systems. We find that for long acoustic wavelengths, the propagation of the SAW is dominated by propagation in the substrate, with a SAW wavelength set by the nanostructure period. However, for shorter acoustic wavelengths, the penetration depth decreases and the SAW is increasingly localized in the nickel, slowing-down the SAW propagation. Our data are in excellent agreement with an effective mass model for thin films, that have been modified to account for the presence of the nanostructure.



**Figure 1:** Setup for ultrafast SAW dispersion measurements. Nickel lines of thickness  $h = 10$  or  $20$  nm, width  $L$  between  $65$  nm and  $2$   $\mu\text{m}$ , and period  $p$  are patterned on a sapphire substrate. An  $800$  nm laser pulse (red) heats the Ni, creating a periodic stress that excites a SAW. This SAW is then probed by observing the dynamically changing diffraction of an ultrafast  $29$  nm EUV pulse (blue) from the surface.

The sample geometry is shown in Fig. 1. A laser heating beam and an EUV probe beam both originate from an ultrafast Ti:Sapphire laser-amplifier system generating  $2\text{mJ}$ ,  $25\text{fs}$  pulses at a wavelength of  $800\text{nm}$  and at a repetition rate of  $2\text{kHz}$ . The output of this laser is split into pump and probe beams. To generate the  $29$  nm probe beam, part of the  $800$  nm light is focused into a gas-filled hollow waveguide to generate high-order harmonics, which are then refocused onto the sample using a grazing-incidence toroidal mirror. The  $800$  nm pump beam is sent through a computer-controlled time-delay stage before being loosely focused onto the sample. A relatively large pump spot ( $\sim 700\mu\text{m}$ ) is used so that the area probed will see a uniform heating fluence of  $2\text{mJ}/\text{cm}$ .

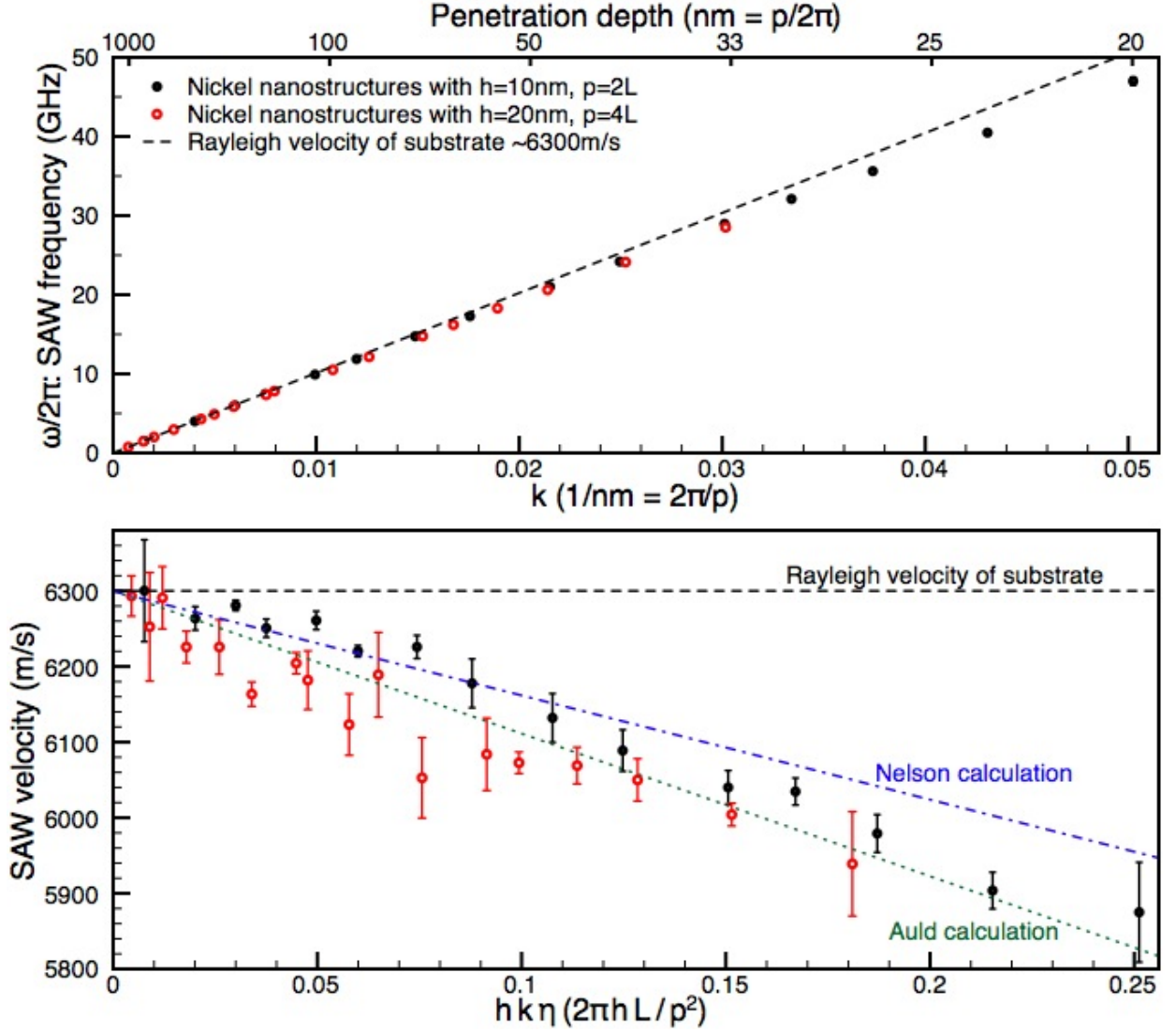
Sapphire was selected as the substrate material because it has a very high acoustic velocity (Rayleigh velocity  $v_{\text{Sa}} \sim 6300 \text{ m/s}$ ) and is transparent to the 800 nm pump light used for exciting the nanostructure. Nickel lines were manufactured using electron beam lithography and liftoff in  $120 \mu\text{m} \times 120 \mu\text{m}$  square regions. Within each region, the lines were  $120 \mu\text{m}$  long with a fixed width  $L$  between 65 and 2000 nm (period confirmed using a SEM). Two grating geometries were used: one with nickel strips of height  $h=20 \text{ nm}$  with period  $p=4L$ , the other with  $h=10 \text{ nm}$  and  $p=2L$ . Because the sapphire substrate is transparent to the 800 nm pump light, the pump pulse only heats the Ni nanostructure. The heat-induced periodic stress launches SAWs that travel along the surface perpendicular to the orientation of the nickel lines. These SAWs interact with the nanostructured nickel strips as they travel, slow down (since the SAW velocity in nickel is slower than in sapphire), and displace the nanostructure surface. The small displacements are detected as changes in the diffraction efficiency of the probe EUV beam. By measuring the change in diffraction as a function of pump-probe delay time, we can observe the dynamic propagation of the SAW. Four scans with  $p=3 \mu\text{m}$ ,  $1.5 \mu\text{m}$ ,  $300 \text{ nm}$ , and  $160 \text{ nm}$  are shown in Fig. 2. The rise and subsequent decay in the signal are due to thermal expansion and subsequent dissipation of heat from the nanostructure into the substrate [9], while the oscillation is due to SAW propagation. The relative amplitude of the SAW component of the signal is  $\sim 5$ - $10\times$  larger than in a similar experiment using an optical probe [6]. For a given grating period  $p$ , we fit the data as shown in Fig. 2 to a sum of the thermal decay and  $\sin^2(\pi vt)$ , where  $v$  is the SAW frequency.



**Figure 2:** Sample SAW data for dynamic EUV probing of surface acoustic waves. Linewidths of  $L=800$  nm and periodicity  $p=1.5$  and  $3 \mu\text{m}$  (top) and  $L=80$  nm and  $p=300$  and  $160$  nm (bottom) were heated and probed. The general shape of the curve corresponds to impulsive heating, followed by a slow thermal decay with a fast SAW oscillation superimposed. The SAW frequencies are shown in the insets.

Past work on acoustic dynamics in a nanostructure has focused on whether the observed signal is dominated by SAW propagation in the substrate or normal mode resonance of individual wires [4, 5, 7]. To determine the relative contribution of these modes, we compared the results from the  $p=4L$  samples to those from  $p=2L$  samples, as shown in Fig. 2. For  $L=800$  nm, SAWs in the  $2L$  ( $p=1.5\mu\text{m}$ ) sample have a frequency of  $4.01 \pm 0.01$  GHz, which are two times greater than the  $2.01 \pm 0.01$  GHz frequency in the  $4L$  ( $p=3\mu\text{m}$ ) samples. The frequency of oscillation is proportional to the nickel strip period rather than the line width. We therefore

conclude that the oscillation is due to SAW propagation in the substrate, with a SAW wavelength set by the strip period ( $\Lambda=p$ ).



**Figure 3:** Measured SAW frequency (top) and velocity (bottom) for propagation in two sets of samples with nanopatterned Ni on sapphire. Significant deviation from the Rayleigh velocity in sapphire is observed in the case of the smaller grating periods. The measured velocity dispersion agrees with an effective mass-loading calculation [11, 12].

We repeated this measurement on structures with different line widths to determine the dispersion curve of the SAW propagation in the Ni/sapphire structure (Fig 3). For long acoustic

wavelengths (large  $p$ , small  $k$ ), the penetration depth is long, so the nanostructure can be ignored and the SAW velocity is the Rayleigh velocity in the sapphire substrate i.e. frequency  $v=v_{sa}/p$ , shown as a dashed line in Fig. 3. For shorter acoustic wavelengths, the penetration depth (see top x-axis in Fig. 3) is decreased and the SAW is increasingly localized in the nickel, slowing-down the SAW propagation. This velocity dispersion of SAWs with wavelengths as short as 125nm is observed here for the first time in such nanostructures: previous studies of Al/quartz [5] and Al/Si [6] structures at isolated acoustic wavelengths  $\sim \Lambda > 200\text{nm}$  suggested that the SAW dispersion is minimal. The data show a small offset between the two different samples, which we attribute to a small difference in the actual duty cycle. The  $v=47$  GHz frequency of the  $p=125\text{nm}$  structure is the highest SAW frequency and shortest SAW wavelength measured optically.

A quantitative calculation of SAW propagation is complicated by the modified Brillouin zone, stopbands, and multi-mode propagation introduced by the nanostructure [10]. To first approximation, an effective mass model from thin film theory based on a perturbative expansion of the stress at the surface can be used [11]. Datta and Hunsinger suggested an extension of this thin film theory to nanostructures, introducing a duty cycle factor “ $\eta$ ” ( $\eta=L/p$ ) by which the dispersion effect is multiplied [12]. Our data is in excellent agreement with this theory over the entire range of wavelengths (Fig. 3, bottom). These results will be useful in eliminating nanostructure-induced errors in similar measurements of thin film properties.

In conclusion, we used ultrafast, coherent, EUV beams to measure high frequency surface acoustic wave propagation and dispersion in nanostructures at frequencies up to  $\sim 50$  GHz for the first time. This technique of visible laser excitation and EUV probing can easily be extended to even shorter wavelengths (higher frequencies), limited only by lithographic



capabilities. Thus, it holds promise for studying materials and interface properties of extremely thin films and interfaces.

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